Bio-Physical Coupling Of Predator-Prey Interactions

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LONG-TERM GOAL

Our long-term goal is to understand the biological and physical processes involved in copepod's feeding in sufficient detail to quantitatively predict predator-prey interactions.

OBJECTIVES

It is difficult to obtain detailed measurements of the three-dimensional flow field around a feeding and/or swimming copepod using current observational methods; however, in order to better understand the physics and the biology at the scale of individual copepod, such three-dimensional velocity fields are needed. We have successfully achieved our first objective, i.e. to use methods of direct numerical simulations to calculate the flow field around a feeding and/or swimming copepod. Based on three-dimensional flow fields around copepods with various behaviors, our next research objective is to test the many hypotheses concerning feeding processes, swarming behaviors as well as sensory mechanisms of copepods. Also, with the knowledge of three-dimensional flow fields around copepods, we can couple the effect of the small-scale fluid mechanics into a direct numerical simulation (DNS) modeling of turbulence and study the effect of turbulence on copepod’s feeding. These calculations will augment and extend the direct observations, making it possible to identify the fundamental aspects of the morphology and operation of predators and prey.

APPROACH

Simulations of the flow, at the scale of individual copepod, have been performed by employing a state-of-the-art, finite-volume code with curvilinear body-fitted coordinates (BFC). This code has the ability

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to handle complex boundary conditions and therefore can smoothly describe the body shape of copepod without the jagged edges that would arise with Cartesian coordinates. The generation of the feeding current is due to the complex movement of copepod's feeding current-generating appendages as well as the swimming behavior of copepod. The effect of the appendages is represented by applying distributed forces to the water adjacent to the copepod. Through adopting appropriate boundary conditions for the computational domain, the swimming and feeding behavior of copepod can be modeled. In order to visualize the modeled three-dimensional flow field, a particle-tracking algorithm is used to track particles and the resulting streamtube is drawn. In addition, vorticity and viscous dissipation rate for the calculated flow field as well as the hydrodynamic forces acting by water on copepod's body can be calculated from the data output from the model.

The hydrodynamic interaction between two copepods can also be studied by this numerical method. Basically, the flow fields around two copepods with various relative positions and distances between the two are calculated, energetic expenses are examined and flow fields are visualized by tracking particles.

Simulations at larger scales will be performed with a code for direct numerical simulation (DNS) of turbulent flow. This code can include stratification. In those calculations the tracking of predators and prey will be based on solving appropriate ordinary differential equations for each "particle". The ordinary differential equations for predators will include the effect of small-scale fluid mechanics coming from the numerical simulation of flow at the scale of individual copepod. We plan to track large samples of predator and prey trajectories, as they evolve with a three-dimensional unsteady turbulent velocity field.

WORK COMPLETED

Testing of the finite-volume code was completed. It has been shown that the code is good for being used to model the low Reynolds number flow around a copepod.

The feeding current around a tethered copepod *Euchaeta norvegica* was successfully modeled. The work acted as a demonstration of the numerical method for modeling the flow field around a copepod. The numerical feeding current was compared to available observational results and good agreement was obtained. The results have been published (Jiang *et al.*, 1999).

The hydrodynamic interaction between two copepods has been studied through numerical simulations. Interesting conclusions have been made for swarming copepods based on this work.

RESULTS

Our three-dimensional, numerical simulations of the feeding current around a tethered copepod *Euchaeta norvegica* showed that the direct numerical simulation of the feeding current around a copepod is possible. The calculated three-dimensional velocity field (Figure 1) is comparable to direct observations. The entrainment region, as visualized by tracking particles in the feeding current and by plotting the resulting streamtube, is quite large (Figure 2). The result can be used to quantify how the copepod takes advantage of the feeding current to trap the algal particles into its capture area. The configuration of the feeding current near to the body surface of the copepod is controlled by how the copepod forces the feeding current and by the copepod's morphology. These parameters were varied and their effects studied in a systematic manner. Specifically, by comparing various spatial distributions of the same amount of total force, it was

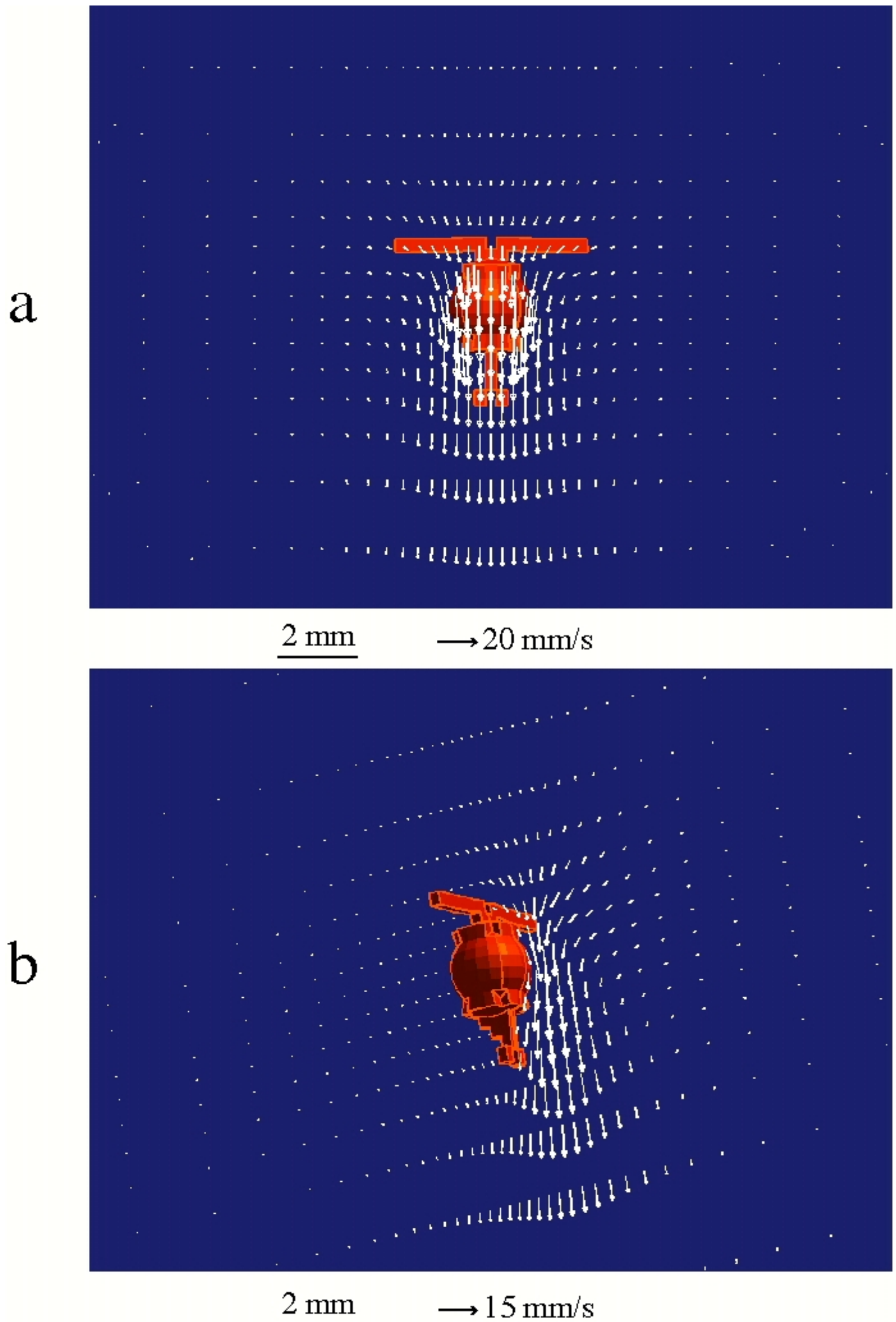

Figure 1. Velocity field for the simulated feeding current. (a) Ventral view, the velocity vectors are in the plane with x=1.6 mm in front of the copepod; (b) Lateral view, the velocity vectors are in the median plane y=0.0.

shown that a distributed force dissipates less energy (and increases the entrainment rate) than a concentrated force, it is thus energetically more desirable. Variations of the copepod's body shape and of the distribution of forces showed little effect on the far field of the feeding current, and therefore do

not appear to affect the detectability by other mechano-receptional organisms. The length scale of the influence field of the feeding current was shown to be anisotropic in three directions, extending 5-7 mm
above or ventrally to the copepod, less than 1 mm dorsally to the copepod, and more than 1 cm down from the abdomen. The results also suggest that the net reaction force on the copepod from the feeding current is of the same order of magnitude as the excess weight of the copepod, but is not sufficient to balance the excess weight completely.

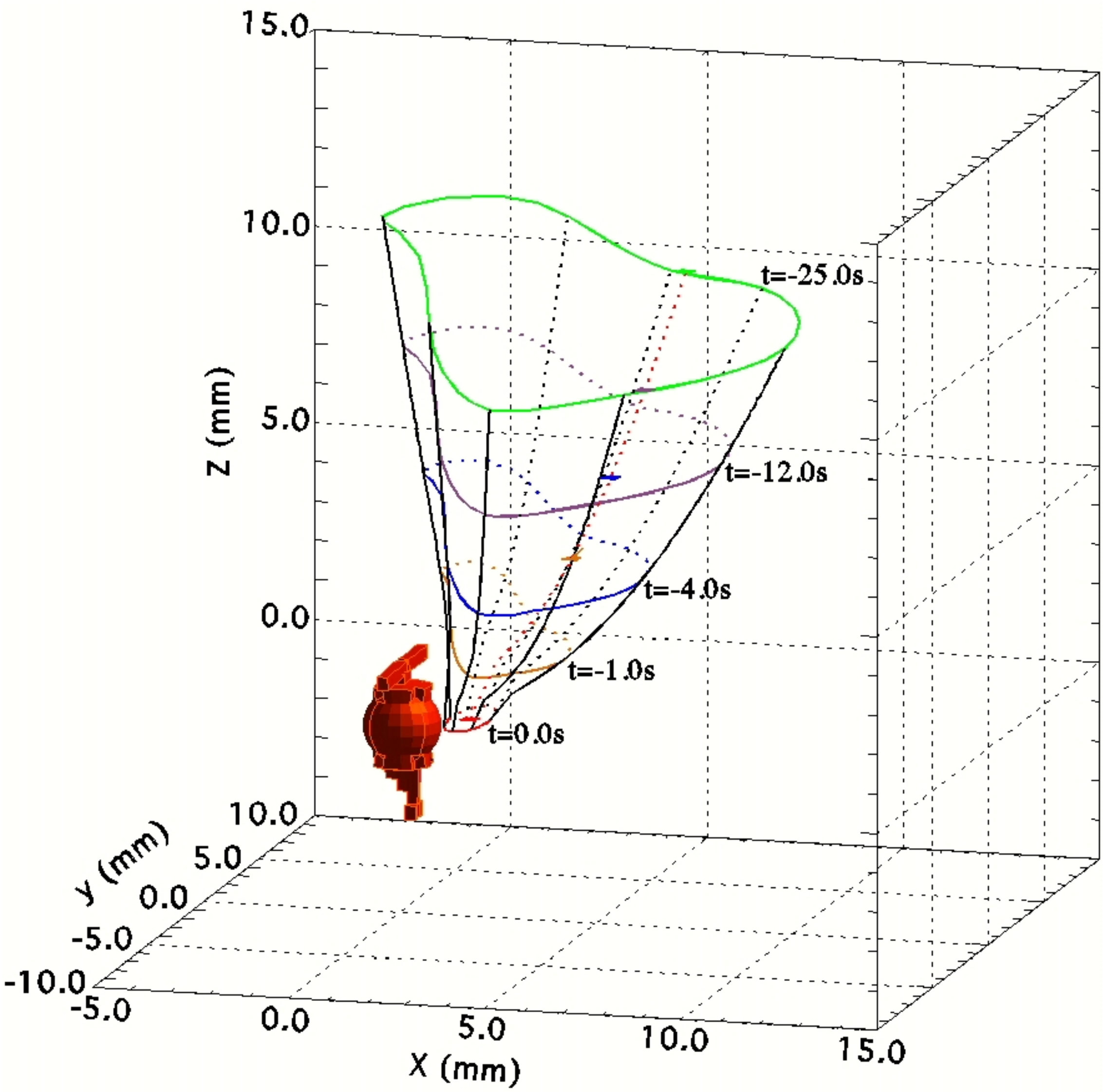

Figure 2. A streamtube in front of the copepod, which is calculated from the simulated feeding current. The time integration for particle tracking is from t=0.0s to t=-25.0s. The red-colored ellipse labeled as t=0.0s is the capture area of the copepod. The yellow-colored closed curve labeled as t=-1.0s is the positions of particles at 1 second before they reach the capture area, and so on for t=-4.0s, t=-12.0s, and t=-25.0s. In order to express the 3-D structure of the streamtube, the center of the capture area (the red star) is tracked from t=0.0s to t=-25.0s, the positions are connected by the red-colored line. The yellow star is the position at t=-1.0s, the blue star is the position at t=-4.0s, the violet star is the position at t=-12.0s, and the green star is the position at t=25.0s.

The results from studying the hydrodynamic interaction between two feeding and/or swimming copepods showed that there exists strong hydrodynamic interference between two copepods in close proximity. However, the results from calculating the power and volumetric flux revealed no energetic advantage for swarming copepods. The hydrodynamic interaction between two copepods changes force balances on both. The patterns of streamtubes for two copepods close to each other suggested that hydrodynamic interaction might interfere each copepod's independent feeding. Thus, they try to avoid strong interference positions such as the places directly above or below another copepod (Figure 3). Close interaction between copepods does not increase the capture rate. Good strategy for swarming copepods is to remain suitable distances away from others and frequently change swimming direction.

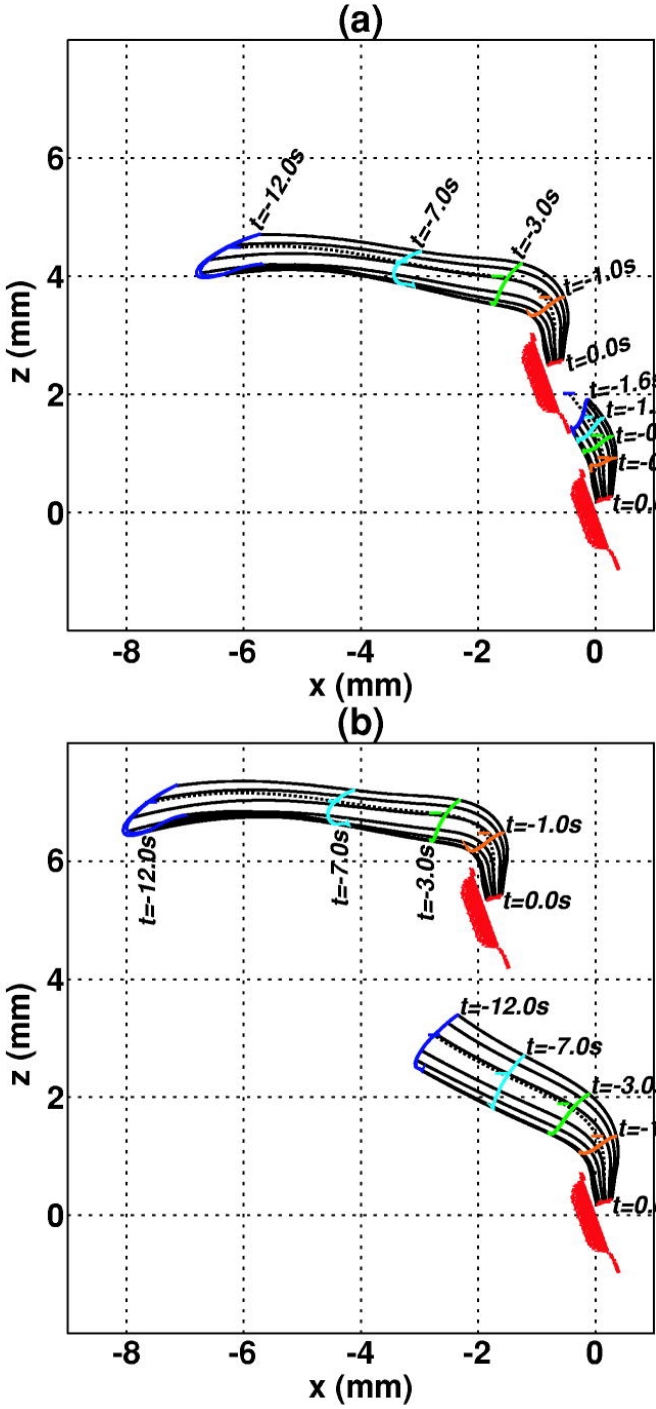

Figure 3. Lateral view of two streamtubes, each of them through a copepod's capture area. Note that the two copepods are one above the other and swim in negative x-direction at a speed of 1.5 mm s^{-1}. The reference system is fixed on the body of one of the two copepods. (a) The distance between the two copepods is 1.16 mm. (b) The distance between the two copepods is 4.18 mm.

IMPACT/APPLICATION

Our work is the first attempt to use methods of direct numerical simulations to reproduce the three-dimensional flow field around a copepod and demonstrates that the direct calculation of the feeding current around a copepod is possible. Computations of the feeding current give details that are difficult to obtain from direct observations. Thus, the calculations expand the value of the laboratory measurements by increasing the spatial and temporal resolution of the role of the feeding currents in the predator-prey interactions. The means by which we have analyzed the calculated data is novel and may also be appropriate for direct observational work. The numerical method can be modified to study many problems in feeding strategy, swarming behavior and sensory physiology, and so on. Its application to biological research is promising.

The study of the oceanic predator-prey interactions, by combining knowledge about plankton and oceanic environment within a framework of numerical simulations, furthers our understanding of the population dynamics in species specific settings. The work shows what is generic about shape, behavior, feeding strategy and feeding success.

PUBLICATIONS

Jiang,H., Meneveau,C., and Osborn,T.R. 1999: Numerical study of the feeding current around a copepod. *J. Plankton Res.*, 21, 1391-1421.

Jiang,H., Osborn,T.R., and Meneveau,C. 1999: Hydrodynamic interaction between two copepods with feeding currents: A numerical study. (in preparation).